Foundation of Cryptography, Lecture 6
Interactive Proofs and Zero Knowledge
Handout Mode

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Part I

Interactive Proofs

$\mathcal{NP}$ as a Non-interactive Proofs

Definition 1 ($\mathcal{NP}$)

$\mathcal{L} \in \mathcal{NP}$ iff $\exists \ell \in$ poly and poly-time algorithm V such that:

- $\forall x \in \mathcal{L} \cap \{0,1\}^n$ there exists $w \in \{0,1\}^{\ell(n)}$ s.t. $\mathsf{V}(x,w) = 1$
- $\mathsf{V}(x,w) = 0$ for every $x \notin \mathcal{L}$ and $w \in \{0,1\}^*$

- A non-interactive proof
- Interactive proofs?

Interactive protocols

- Interactive algorithm
- Protocol $\pi = (A, B)$
- RV describing the parties joint output $\langle A(i_A), B(i_B) \rangle (i) \rangle$
- *m*-round algorithm, *m*-round protocol

Interactive Proofs

> **Definition 2 (Interactive Proof (IP))**
>
> A protocol (P, V) is an interactive proof for $\mathcal{L}$, if V is PPT and:
>
> **Completeness** $\forall x \in \mathcal{L}$, $\Pr[\langle (P, V)(x) \rangle = 1] \geq 2/3$
>
> **Soundness** $\forall x \notin \mathcal{L}$, and any algorithm P^* $\Pr[\langle (P^*, V)(x) \rangle = 1] \leq 1/3$

- $\text{IP} = \text{PSPACE}$!
- We typically consider (and achieve) perfect completeness
- Negligible "soundness error" achieved via repetition.
- Sometime we have efficient provers via "auxiliary input"
- *computationally sound proofs/interactive arguments*: Soundness only guaranteed against efficient (PPT) provers

Section 1

Interactive Proof for Graph Non-Isomorphism

Graph isomorphism

Π_m – the set of all permutations from $[m]$ to $[m]$

> **Definition 3 (graph isomorphism)**
>
> Graphs $G_0 = ([m], E_0)$ and $G_1 = ([m], E_1)$ are isomorphic, denoted $G_0 \equiv G_1$, if $\exists \pi \in \Pi_m$ such that $(u, v) \in E_0$ iff $(\pi(u), \pi(v)) \in E_1$.

- We assume a reasonable mapping from graphs to strings
- $\mathcal{GI} = \{(G_0, G_1) \colon G_0 \equiv G_1\} \in \mathcal{NP}$
- Does $\mathcal{GNI} = \{(G_0, G_1) \colon G_0 \not\equiv G_1\} \in \mathcal{NP}$?
- We will show a simple interactive proof for $\mathcal{GNI}$ Idea: Beer tasting...

Protocol 4 ((P, V))

Common input $G_0 = ([m], E_0), G_1 = ([m], E_1)$

1. V chooses $b \leftarrow \{0, 1\}$ and $\pi \leftarrow \Pi_m$, and sends $\pi(E_b) = \{(\pi(u), \pi(v)) \colon (u, v) \in E_b\}$ to P
2. P send b' to V (tries to set $b' = b$)
3. V accepts iff $b' = b$

Claim 5

The above protocol is IP for $\mathcal{GNI}$, with perfect completeness and soundness error $\frac{1}{2}$.

Proving Claim 5

- Graph isomorphism is an equivalence relation (separates the set of all graph pairs into separate subsets)
- $([m], \pi(E_i))$ is a random element in $[G_i]$ — the equivalence class of G_i

Hence,

$G_0 \equiv G_1$: $\Pr[b' = b] \leq \frac{1}{2}$.

$G_0 \not\equiv G_1$: $\Pr[b' = b] = 1$ (i.e., P can, possibly inefficiently, extracted from $\pi(E_i)$)

□

Part II

Zero knowledge Proofs

Where is Waldo?

Question 6

Can you prove you know where Waldo is without revealing his location?

The concept of zero knowledge

- Proving w/o revealing any addition information.
- What does it mean?
  Simulation paradigm.

Zero knowledge Proof

Definition 7 (computational $\mathcal{ZK}$)

An interactive proof (P, V) is computational zero-knowledge proof ($\mathcal{CZK}$) for $\mathcal{L}$, if $\forall$ PPT V^*, $\exists$ PPT S such that $\{\langle(\mathsf{P}, \mathsf{V}^*)(x)\rangle\}_{x \in \mathcal{L}} \approx_c \{\mathsf{S}(x)\}_{x \in \mathcal{L}}$.
Perfect $\mathcal{ZK}$ ($\mathcal{PZK}$)/statistical $\mathcal{ZK}$ ($\mathcal{SZK}$) – the above dist. are identicallly/statistically close, even for unbounded V^*.

1. $\mathcal{ZK}$ is a property of the prover.
2. $\mathcal{ZK}$ only required to hold with respect to true statements.
3. wlg. V^*'s outputs is its "view".
4. Trivial to achieve for $\mathcal{L} \in \mathcal{BPP}$
5. Extension: auxiliary input
6. The "standard" $\mathcal{NP}$ proof is typically not zero knowledge
7. Next class — $\mathcal{ZK}$ for all $\mathcal{NP}$

Section 2

Zero-Knowledge Proof go Graph-Isomorphism

$\mathcal{ZK}$ **Proof for Graph Isomorphism**

Idea: route finding

Protocol 8 ((P, V))

Common input $x = (G_0 = ([m], E_0), G_1 = ([m], E_1))$

  P's input a permutation π such that $\pi(E_1) = E_0$

1. P chooses $\pi' \leftarrow \Pi_m$ and sends $E = \pi'(E_0)$ to V
2. V sends $b \leftarrow \{0, 1\}$ to P
3. if $b = 0$, P sets $\pi'' = \pi'$, otherwise, it sends $\pi'' = \pi' \circ \pi$ to V
4. V accepts iff $\pi''(E_b) = E$

Claim 9

The above protocol is $\mathcal{SZK}$ for $\mathcal{GI}$, with perfect completeness and soundness $\frac{1}{2}$.

- Completeness: Clear
- Soundness: If exist $j \in \{0, 1\}$ for which $\nexists \pi' \in \Pi_m$ with $\pi'(E_j) = E$, then V rejects w.p. at least $\frac{1}{2}$.
  Assuming V rejects w.p. less than $\frac{1}{2}$ and let π_0 and π_1 be the values guaranteed by the above observation (i.e., mapping E_0 and E_1 to E respectively).
  Then $\pi_0^{-1}(\pi_1(E_1)) = \pi_0 \implies (G_0, G_1) \in \mathcal{GI}$.
- $\mathcal{ZK}$: Idea – for $(G_0, G_1) \in \mathcal{GI}$, it is easy to generate a random transcript for Steps 1-2, and to be able to open it with prob $\frac{1}{2}$.

The simulator

For a start consider a deterministic cheating verifier V^* that never aborts.

Algorithm 10 (S)

Input: $x = (G_0 = ([m], E_0), G_1 = ([m], E_1))$
Do $|x|$ times:

1. Choose $b' \leftarrow \{0, 1\}$ and $\pi \leftarrow \Pi_m$, and "send" $\pi(E_{b'})$ to $V^*(x)$.
2. Let b be V^*'s answer. If $b = b'$, send π to V^*, output V^*'s output and halt.
   Otherwise, rewind the simulation to its first step.

Abort

Claim 11

$\{\langle (P, V^*)(x) \rangle\}_{x \in \mathcal{GI}} \approx \{S(x)\}_{x \in \mathcal{GI}}$

Algorithm 12 (S′)

Input: $x = (G_0 = ([m], E_0), G_1 = ([m], E_1))$

Do $|x|$ times:

1. Choose $\pi \leftarrow \Pi_m$ and sends $E = \pi(E_0)$ to $V^*(x)$.

2. Let b be V^*'s answer.
   W.p. $\frac{1}{2}$, find π' such that $E = \pi'(E_b)$ and send it to V^*, output V^*'s output and halt.
   Otherwise, rewind the simulation to its first step.

Abort

Claim 13

$S(x) \equiv S'(x)$ for any $x \in \mathcal{GI}$.

Proof: ?

Proving Claim 11 cont.

Algorithm 14 (S'')

Input: $x = (G_0 = ([m], E_0), G_1 = ([m], E_1))$

1. Choose $\pi \leftarrow \Pi_m$ and sends $E = \pi(E_0)$ to $V^*(x)$.
2. Find π' such that $E = \pi'(E_b)$, send it to V^*, output V^*'s output and halt.

Claim 15

$\forall x \in \mathcal{GI}$ it holds that

1. $\langle (P, V^*(x)) \rangle \equiv S''(x)$.
2. $\mathrm{SD}(S''(x), S'(x)) \leq 2^{-|x|}$.

Proof: ? (1) is clear.

Fix (E, π') and let $\alpha = \Pr_{S''(x)}[(E, \pi')]$.
It holds that

$$\Pr_{S'(x)}[(E, \pi')] = \alpha \cdot \sum_{i=1}^{|x|}(1 - \frac{1}{2})^{i-1} \cdot \frac{1}{2}$$
$$= (1 - 2^{-|x|}) \cdot \alpha$$

Hence, $\mathsf{SD}(S''(x), S'(x)) \leq 2^{-|x|} \square$

Remarks

1. Randomized verifiers
2. Aborting verifiers
3. Auxiliary input
4. Negligible soundness error? Sequentiall/Parallel composition
5. Perfect $\mathcal{ZK}$ for "expected time simulators"
6. "Black box" simulation

Section 3

Black-box Zero Knowledge

Black-box simulators

Definition 16 (Black-box simulator)

(P, V) is $\mathcal{CZK}$ with black-box simulation for $\mathcal{L}$, if $\exists$ oracle-aided PPT S s.t. for every deterministic polynomial-time[a] V^*:

$$\{(P(w_x), V^*(z_x))(x)\}_{x \in \mathcal{L}} \approx_c \{S^{V^*(x,z_x)}(x)\}_{x \in \mathcal{L}}$$

for any $\{(w_x, z_x) \in R_{\mathcal{L}}(x) \times \{0, 1\}^*\}_{x \in \mathcal{L}}$.
Prefect and statistical variants are defined analogously.

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[a]Length of auxiliary input does not count for the running time.

1. "Most simulators" are black box
2. Strictly weaker then general simulation!

Section 4

Zero Knowledge for all NP

$\mathcal{CZK}$ for 3COL

- Assuming that OWFs exists, we give a $\mathcal{CZK}$ for 3COL .
- We show how to transform it for any $\mathcal{L} \in \mathcal{NP}$ (using that 3COL $\in \mathcal{NPC}$).

Definition 17 (3COL)

$G = (M, E) \in$ 3COL, if $\exists\, \phi \colon M \mapsto [3]$ s.t. $\phi(u) \neq \phi(v)$ for every $(u, v) \in E$.

We use commitment schemes.

The protocol

Let π_3 be the set of all permutations over [3]. We use perfectly binding commitment Com .

Protocol 18 ((P, V))

Common input: Graph $G = (M, E)$ with $n = |G|$
P's input: a (valid) coloring ϕ of G

1. P chooses $\pi \leftarrow \Pi_3$ and sets $\psi = \pi \circ \phi$
2. $\forall v \in M$: P commits to $\psi(v)$ using Com (with security parameter 1^n).
   Let c_v and d_v be the resulting commitment and decommitment.
3. V sends $e = (u, v) \leftarrow E$ to P
4. P sends $(d_u, \psi(u)), (d_v, \psi(v))$ to V
5. V verifies that (1) both decommitments are valid, (2) $\psi(u), \psi(v) \in [3]$ and (3) $\psi(u) \neq \psi(v)$.

> **Claim 19**
>
> The above protocol is a $\mathcal{CZK}$ for 3COL, with perfect completeness and soundness $1/|E|$.

- Completeness: Clear
- Soundness: Let $\{c_v\}_{v \in M}$ be the commitments resulting from an interaction of V with an arbitrary P^*.
  Define $\phi \colon M \mapsto [3]$ as follows:
  $\forall v \in M$: let $\phi(v)$ be the (single) value that it is possible to decommit c_v into (if not in [3], set $\phi(v) = 1$).
  If $G \notin 3COL$, then $\exists (u,v) \in E$ s.t. $\psi(u) = \psi(v)$. Hence V rejects such x w.p. a least $1/|E|$

Proving $\mathcal{ZK}$

Fix a deterministic, non-aborting V^* that gets no auxiliary input.

Algorithm 20 (S)

Input: A graph $G = (M, E)$ with $n = |G|$

Do $n \cdot |E|$ times:

1. Choose $e' = (u, v) \leftarrow E$. Set $\psi(u) \leftarrow [3]$, $\psi(v) \leftarrow [3] \setminus \{\psi(u)\}$, and $\psi(w) = 1$ for $w \in M \setminus \{u, v\}$

2. $\forall v \in M$: commit to $\psi(v)$ to V^* (resulting in c_v and d_v)

3. Let e be the edge sent by V^*.
   If $e = e'$, send $(d_u, \psi(u)), (d_v, \psi(v))$ to V^*, output V^*'s output and halt.
   Otherwise, rewind the simulation to its first step.

Abort

Proving $\mathcal{ZK}$ cont.

Claim 21

$\{(\mathsf{P}(w_x), \mathsf{V}^*)(x)\}_{x \in 3\mathrm{COL}} \approx_c \{\mathsf{S}^{\mathsf{V}^*(x)}(x)\}_{x \in 3\mathrm{COL}}$, for any
$\{w_x \in R_{3\mathrm{COL}}(x)\}_{x \in 3\mathrm{COL}}$.

Consider the following (inefficient simulator)

Algorithm 22 (S′)

Input: $G = (V, E)$ with $n = |G|$
Find (using brute force) a valid coloring ϕ of G
Do $n \cdot |E|$ times

1. Act as the honest prover does given private input ϕ

2. Let e be the edge sent by V^*.
   W.p. $1 / |E|$, S′ sends $(\psi(u), d_u), (\psi(v), d_v)$ to V^*, output V^*'s output and halt.
   Otherwise, rewind the simulation to its first step.

Abort

Claim 23

$\{S^{V^*(x)}(x)\}_{x \in \text{3COL}} \approx_c \{S'^{V^*(x)}(x)\}_{x \in \text{3COL}}$

Proof: ?

Proving Claim 23

Assume $\exists$ PPT D, $p \in$ poly and an infinite set $\mathcal{I} \subseteq$ 3COL s.t.

$$\left| \Pr[D(|x|, S^{V^*(x)}(x)) = 1] - \Pr[D(|x|, S'^{V^*(x)}(x)) = 1] \right| \geq 1/p(|x|)$$

for all $x \in \mathcal{I}$.

Hence, $\exists$ PPT R^* and $b \neq b' \in [3]$ such that

$$\{\text{View}_{R^*}(S(b), R^*(x))(1^{|x|})\}_{x \in \mathcal{I}} \not\approx_c \{\text{View}_{R^*}(S(b'), R^*(x))(1^{|x|})\}_{x \in \mathcal{I}}$$

where S is the sender in Com.

We critically used the non-uniform security of Com

S′ is a good simulator

Claim 24

$\{(P(w_x), V^*)(x)\}_{x \in 3COL} \approx_c \{S'^{V^*(x)}(x)\}_{x \in 3COL}$, for any $\{w_x \in R_{\mathcal{GI}}(x)\}_{x \in 3COL}$.

Proof: ?

Remarks

- Aborting verifiers
- Auxiliary inputs
- Soundness amplification
- Non-uniform hiding guarantee

Extending to all $\mathcal{L} \in \mathcal{NP}$

Let (P, V) be a $\mathcal{CZK}$ for 3COL, and let Map_X and Map_W be two poly-time functions s.t.

- $\forall x \in \{0,1\}^*$: $x \in \mathcal{L} \Leftrightarrow \mathsf{Map}_X(x) \in$ 3COL,
- $\forall x \in \mathcal{L}$ and $w \in R_L(x)$: $\mathsf{Map}_W(x, w) \in R_{3COL}(\mathsf{Map}_X(x))$

Protocol 25 ($(P_{\mathcal{L}}, V_{\mathcal{L}})$)

Common input: $x \in \{0,1\}^*$
$P_{\mathcal{L}}$'s input: $w \in R_{\mathcal{L}}(x)$

1. The two parties interact in $\langle (P(\mathsf{Map}_W(x, w)), V)(\mathsf{Map}_X(x)) \rangle$, where $P_{\mathcal{L}}$ and $V_{\mathcal{L}}$ taking the role of P and V respectively.
2. $V_{\mathcal{L}}$ accepts iff V accepts in the above execution.

Extending to all $\mathcal{L} \in \mathcal{NP}$ cont.

> **Claim 26**
>
> $(P_\mathcal{L}, V_\mathcal{L})$ is a $\mathcal{CZK}$ for $\mathcal{L}$ with the same completeness and soundness as (P, V) as for 3COL.

- Completeness and soundness: Clear.
- Zero knowledge: Let S (an efficient) $\mathcal{ZK}$ simulator for (P, V) (for 3COL).
  Define $S_\mathcal{L}(x)$ to output $S(\text{Map}_X(x))$, while replacing the string $\text{Map}_X(x)$ in the output of S with x.
  $\{(P(w_x), V^*)(x)\}_{x \in \mathcal{L}} \not\approx_c \{S_\mathcal{L}^{V^*(x)}(x)\}_{x \in \mathcal{L}}$ for some $V_\mathcal{L}^*$, implies $\{(P(\text{Map}_W(x, w_x)), V^*)(x)\}_{x \in 3COL} \not\approx_c \{S^{V^*(x)}(x)\}_{x \in 3COL}$,
- $V^*(x)$: find $x^{-1} = \text{Map}_X^{-1}(x)$ and act like $V_\mathcal{L}^*(x^{-1})$